Space Launch System Base Heating Test:

Sub-Scale Rocket Engine/Motor Design, Development & Performance Analysis

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Outline

- **Test Program Background & Motivation**
- **ATA-002 Core-Stage Rocket Engine Module (CS-REM)**
  - Design, Development & Performance Analysis
- **ATA-002 Booster Stage Solid Rocket Motor (BSRM)**
  - Design, Development & Performance Analysis
- **CS-REM & BSRM Integrated Test**
- **Conclusions**

ATA-002 Technical Team

- **Aerosciences Branch, NASA Marshall Space Flight Center (MSFC)**
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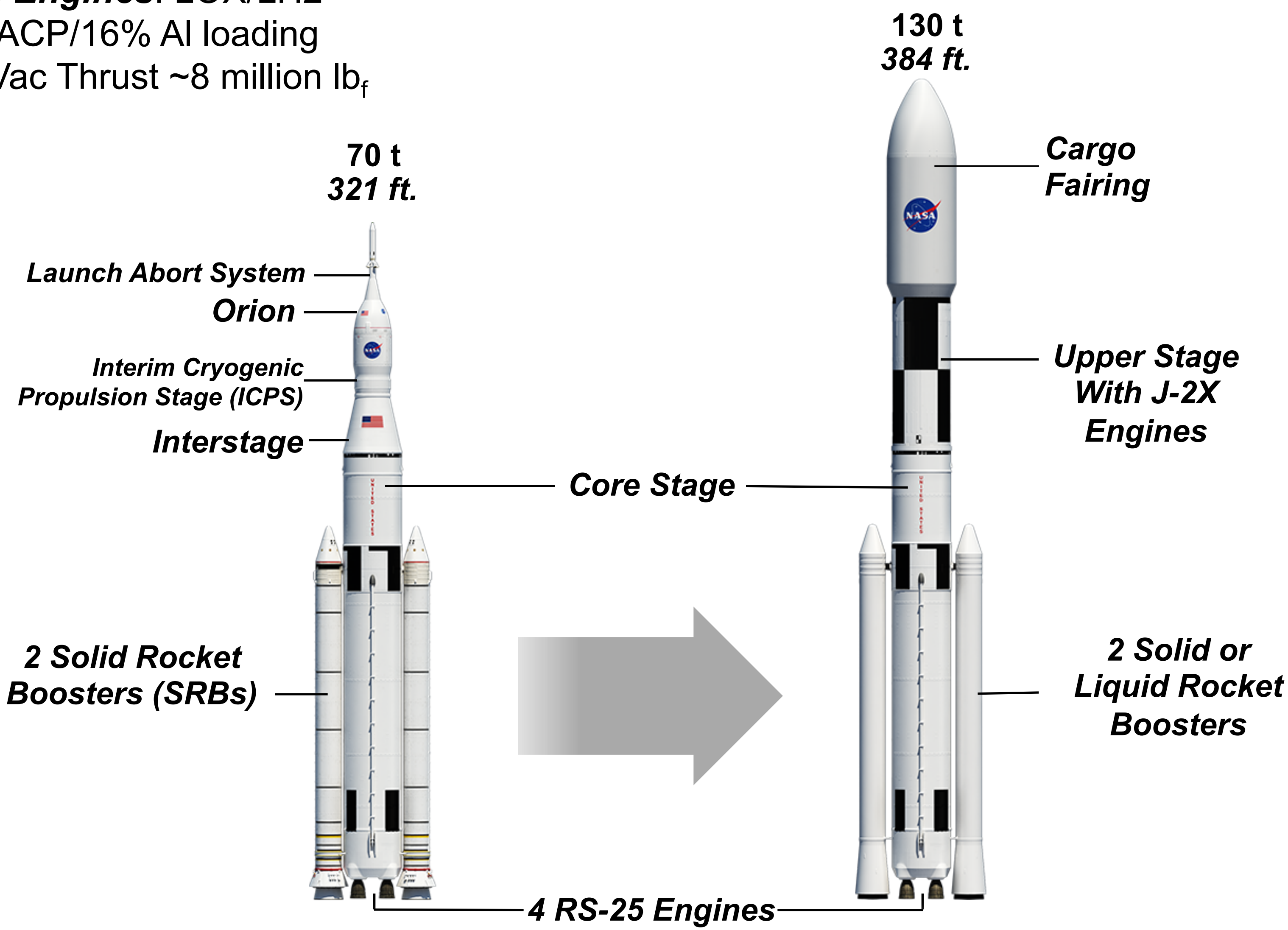
- **Propellants and Propulsion Branch, NASA Glenn Research Center**
  - Bill Marshall
- **Plasma Processes Inc.**
  - Tim McKechnie and George Thom

[1] **NASA Technical Lead**

[2] **CUBRC Technical Lead**

Space Launch System (SLS) Architecture

RS-25 Engines: LOX/LH2
SRB: ACP/16% Al loading
Total Vac Thrust ~8 million lb_f



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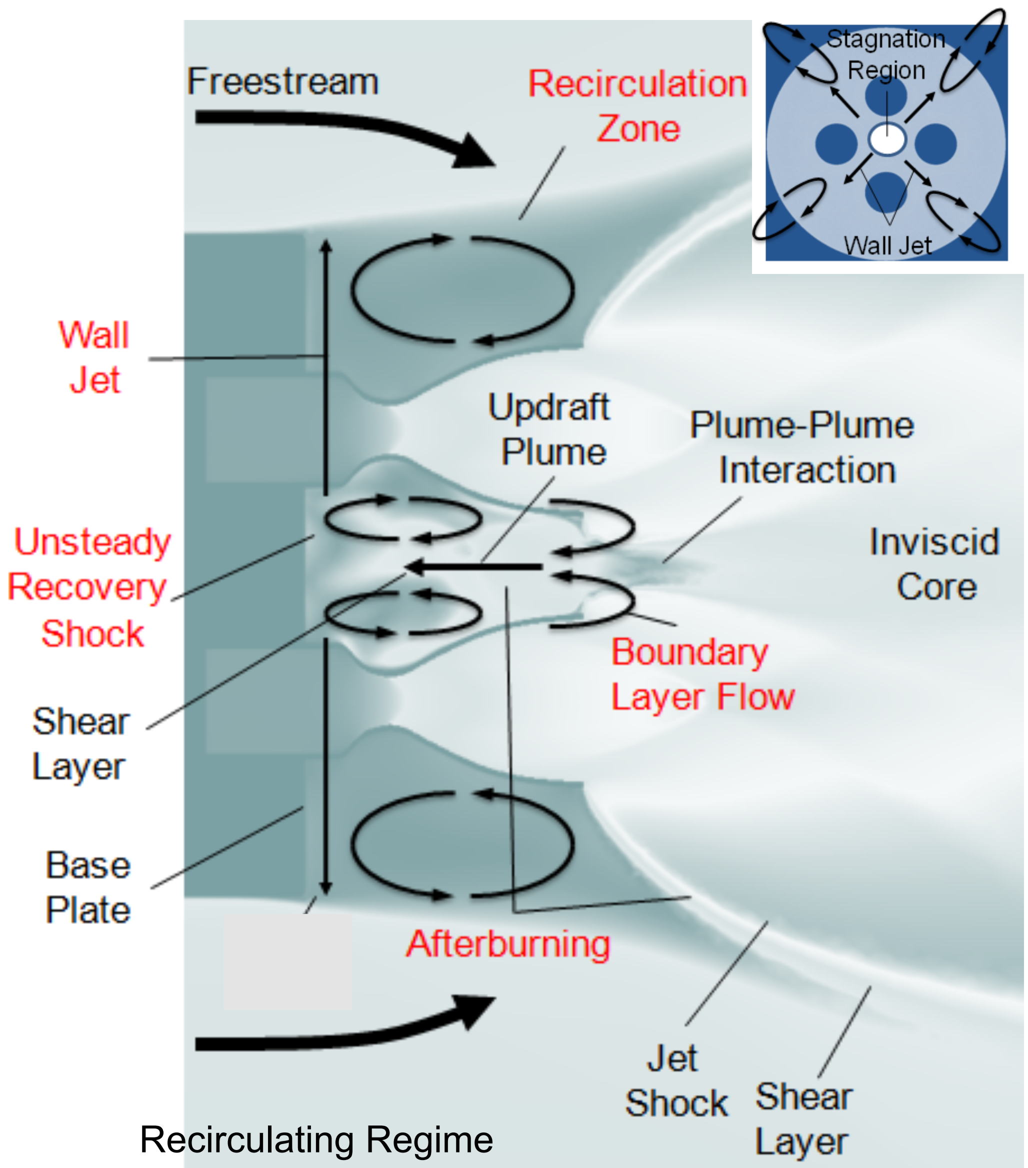
Motivation for Ground Tests

- **Six hot rocket plumes expanding and interacting near the vehicle base**
  - Potential to generate high thermal environments within base and nozzles
- **Base flows demonstrate complex flow physics**
  - No pure analytical methods have been developed for adequate prediction
- **New base geometry and performance requirements for SLS**
  - Cannot blindly use heritage data
- **CFD and semi-empirical methodologies show poor comparisons**
  - Significant deviations in magnitude and trends
- **Accurate base flow environment prediction needed to efficiently size TPS**
  - Decreases vehicle cost and improves crew safety

Base Flow Field – Motivation for Ground Tests



Recirculating Regime

Mehta et al. JSR 2013

Limited numerical and analytical studies have been conducted to fully characterize multi-plume base heating.

For the following reasons:
1. Complex
2. Unsteady
3. Many interacting flow features
4. Leads to many different trends, distributions and deltas

Base Flow Regimes:

Aspirating – Freestream air is entrained by the non-interacting rocket plumes (cooling)

Transitional – slight interactions by adjacent plumes leads to updraft plume component and downward aspirating jet

Recirculating – large interactions by highly expansive plumes leads to predominantly an updraft plume (heating)

ATA-002 SLS Pathfinder Test Program

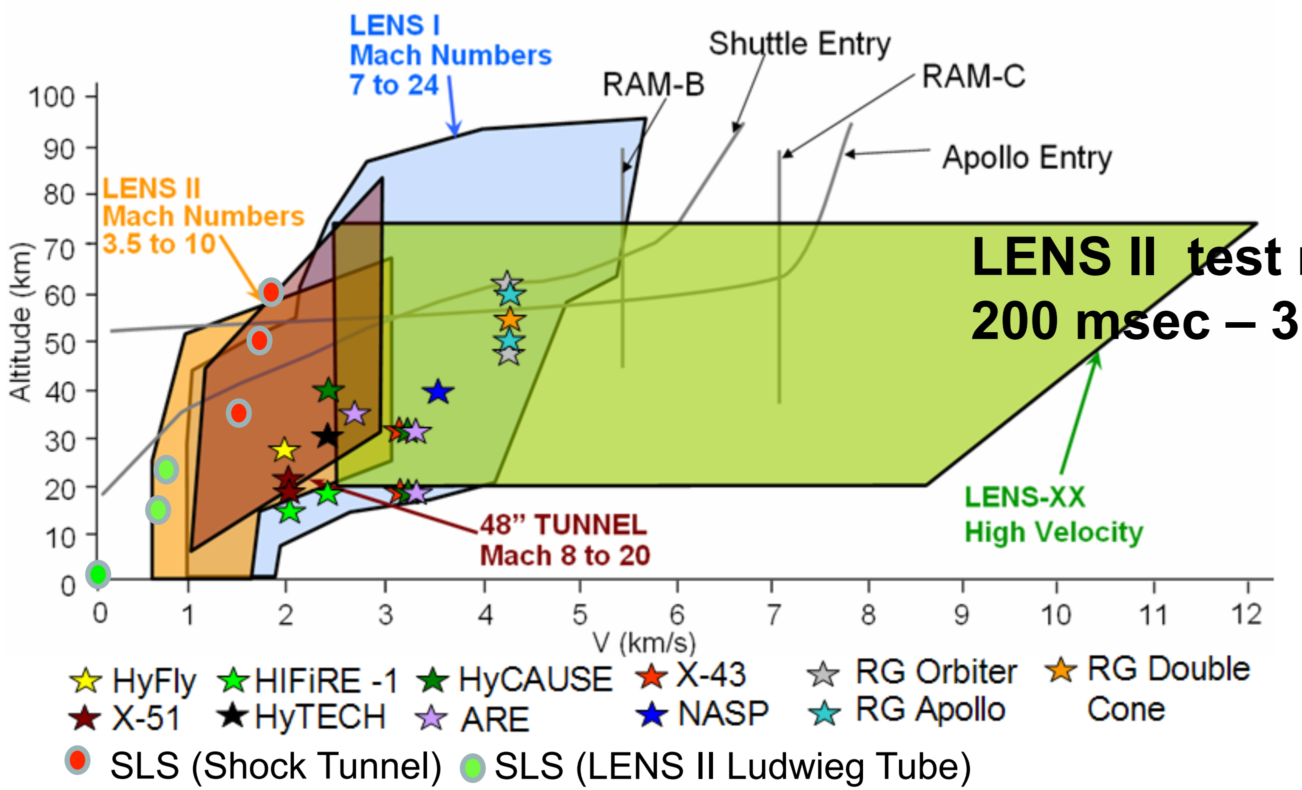
- **ATA-002 Base Heating Test Program is broken down into two sub-test programs: (1) Pathfinder and (2) Main Base Heating Test**
- **Goal is to develop sub-scale SLS propulsion systems similar to full-scale flight system to be used for short-duration (~100 msec) base heating tests.**
- **The Pathfinder Program has many difficult challenges:**
  - Highly complex test program (simulate solid & liquid propulsion systems)
  - Short-duration testing
  - Different configuration/performance than Shuttle Base Heating Models
  - Not attempted in 40 years
  - Limited heritage technical resources (engineers/technicians/components)
  - Limited funding & short schedule as compared to heritage test programs
- **Pathfinder Test Program is the main focus of this paper**

ATA-002 Main Base Heating Test Program

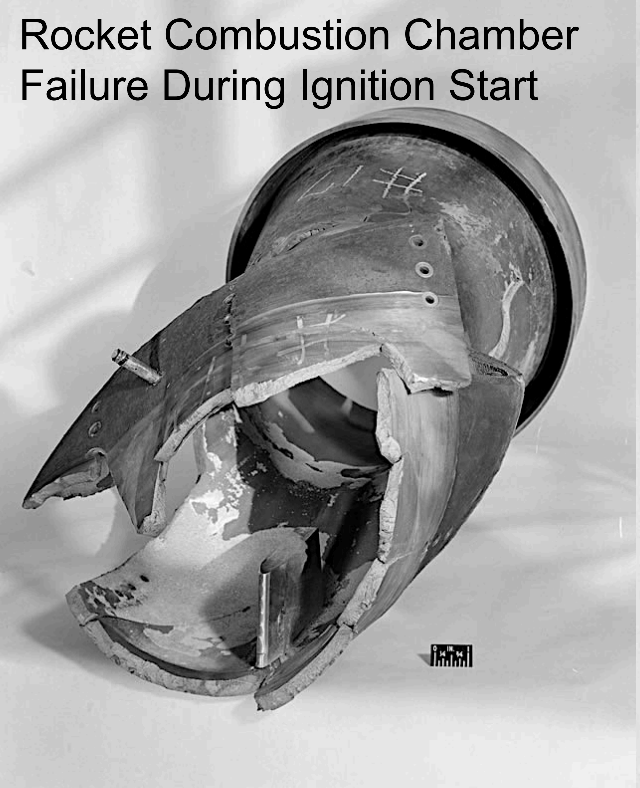
- **Main Goal: To measure base flow and heating characteristics for the SLS1000x vehicle and to scale these measurements for flight predictions**

- **Test Requirements**
  - 2% SLS-1000x Model
  - Test in short-duration test facility – CUBRC LENS II
  - Simulated altitude: 45 kft to 200 kft, Mach 2.5 to 5.5
  - Configuration: full-stack and core-only stage space flight conditions
  - Test Duration: ~100 msec steady-state time window
  - No gimbaling of engines/motors
  - No Angle of Attack
  - Test Engine-Out Case
  - 200 measurements within base and external nozzles

CUBRC LENS Shock Tunnels

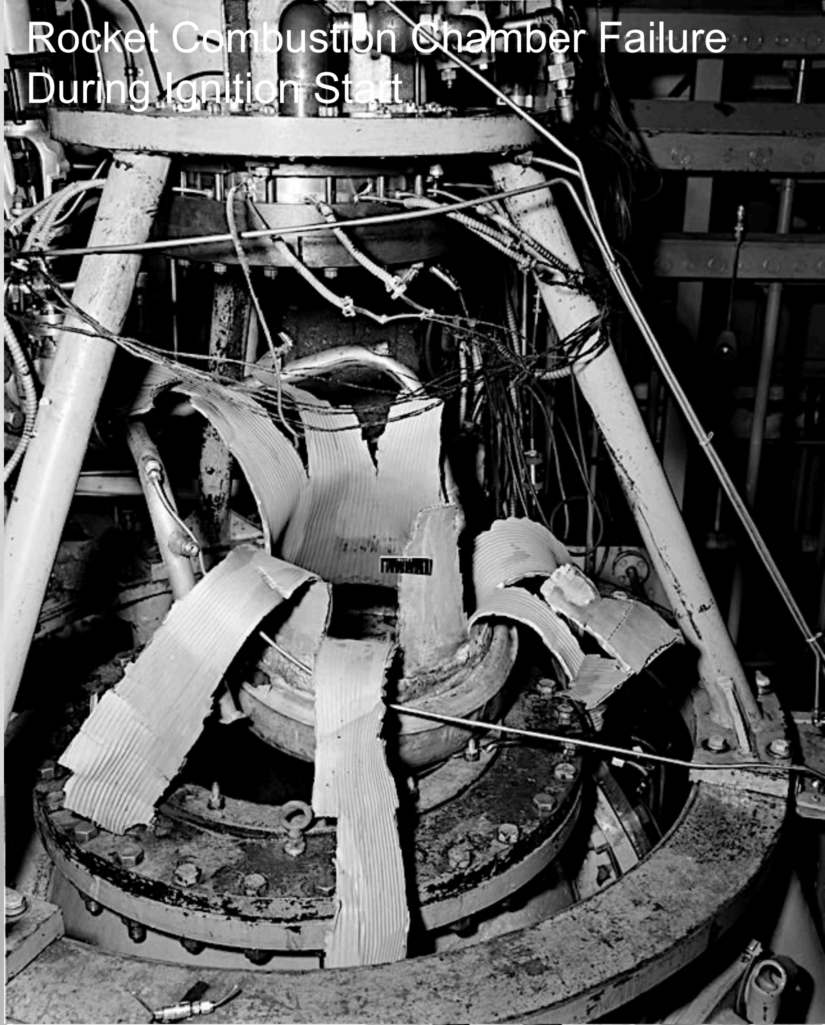


LENS II test run times:
200 msec – 30 msec

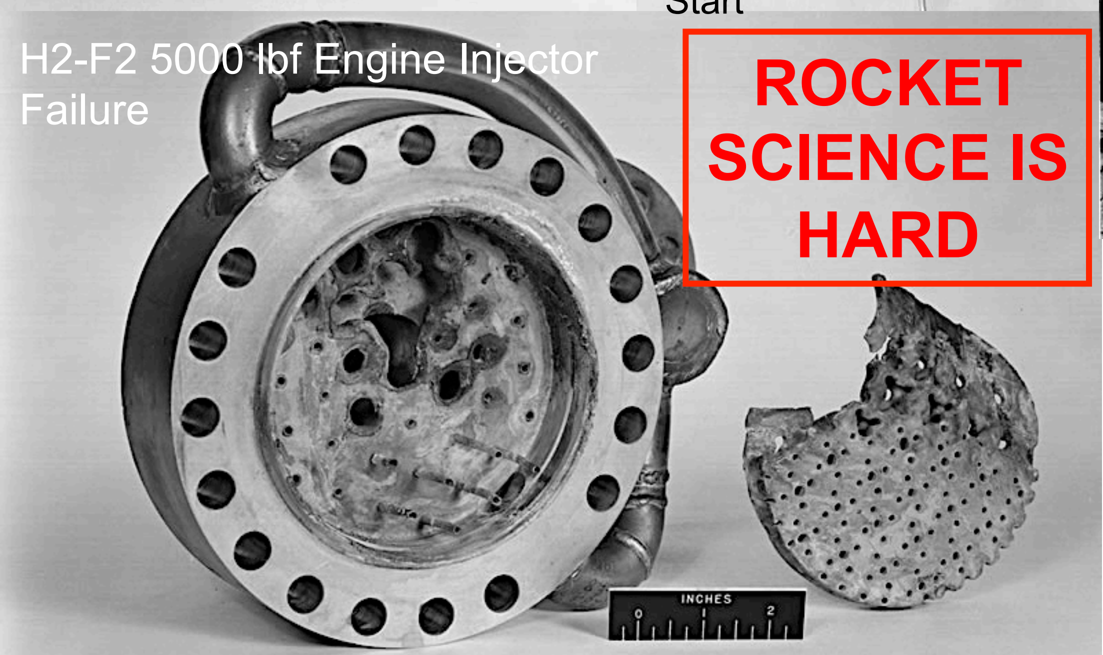


Rocket Combustion Chamber Failure During Ignition Start

Rocket Engine Injector Failure During Ignition Start

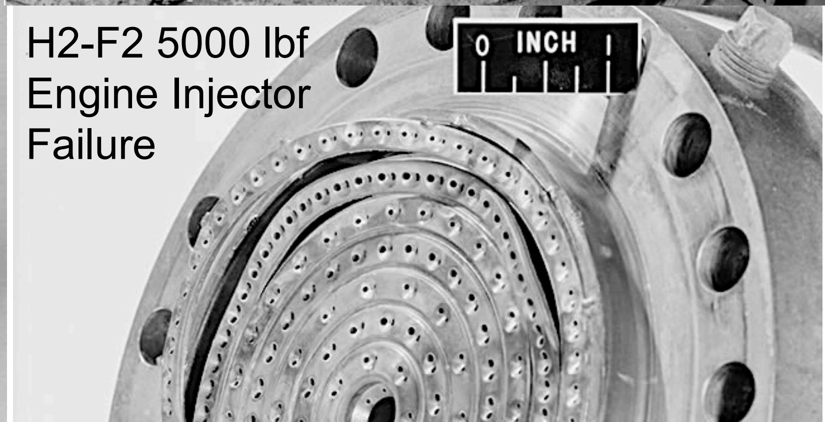


Rocket Combustion Chamber Failure During Ignition Start



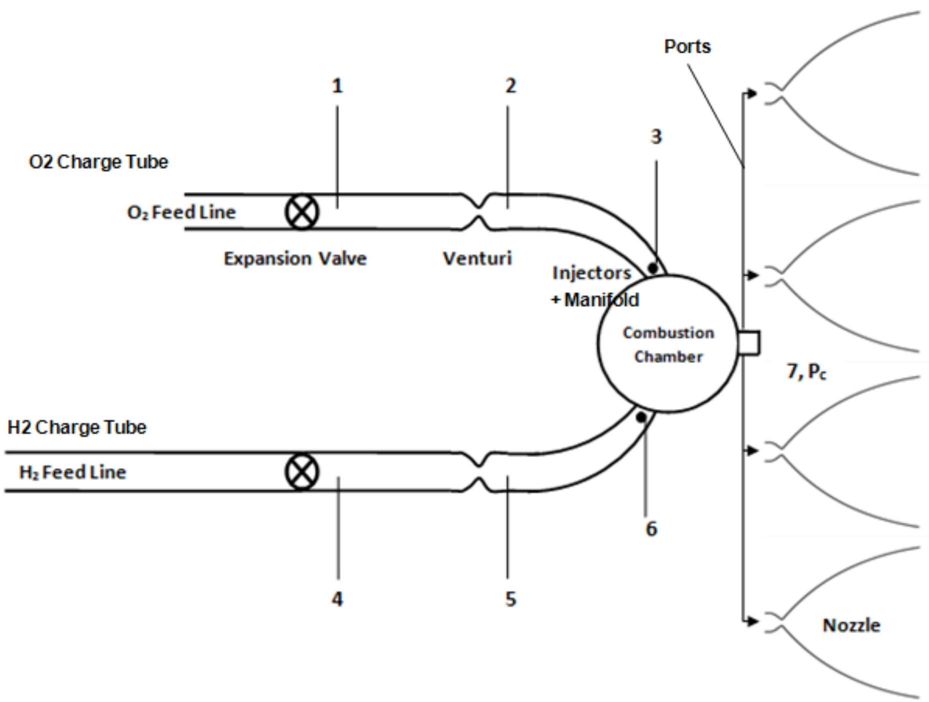
H2-F2 5000 lbf Engine Injector Failure

ROCKET SCIENCE IS HARD



H2-F2 5000 lbf Engine Injector Failure

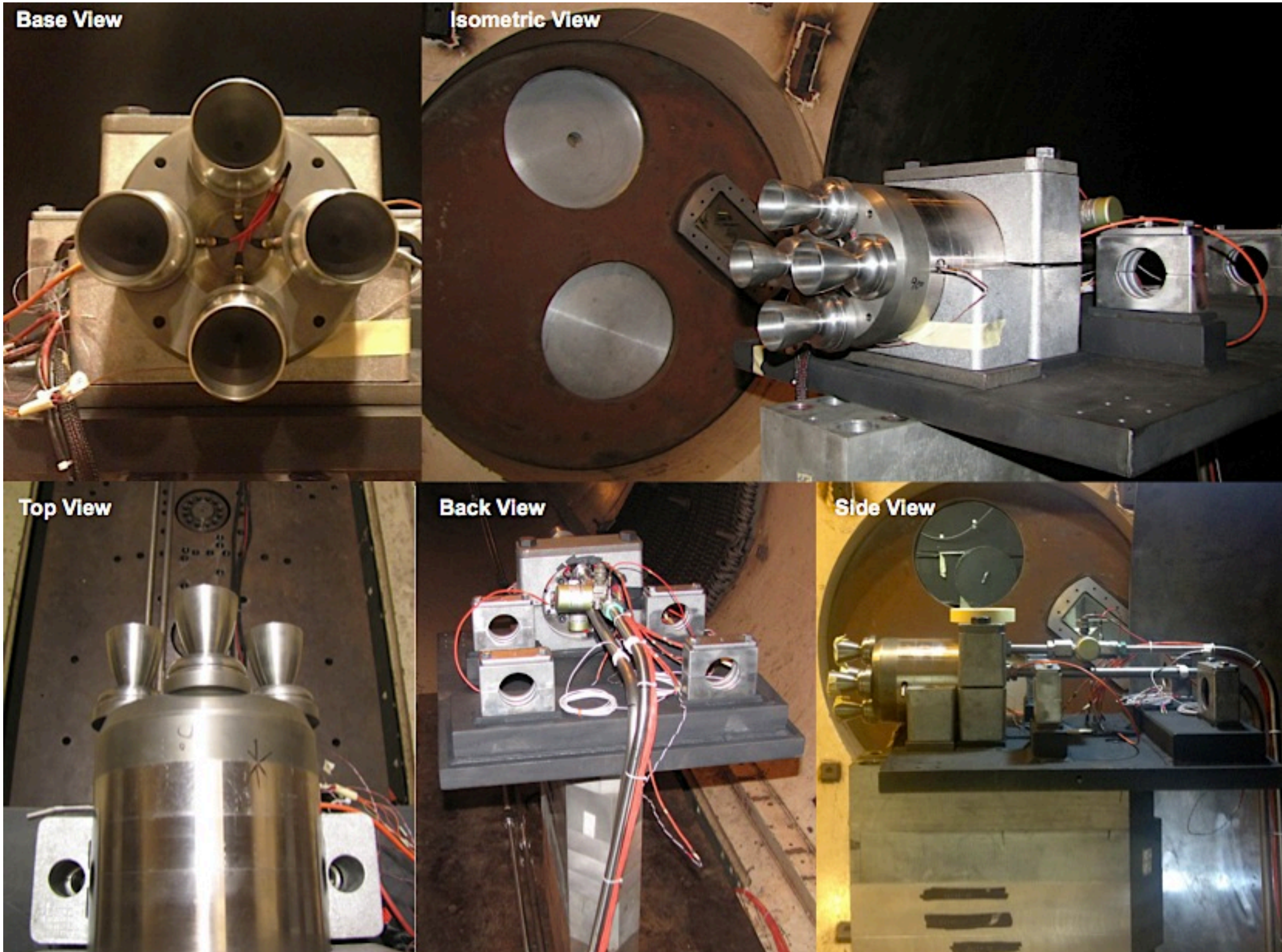
ATA-002 Core-Stage (CS) Rocket Engine Module (REM) Design



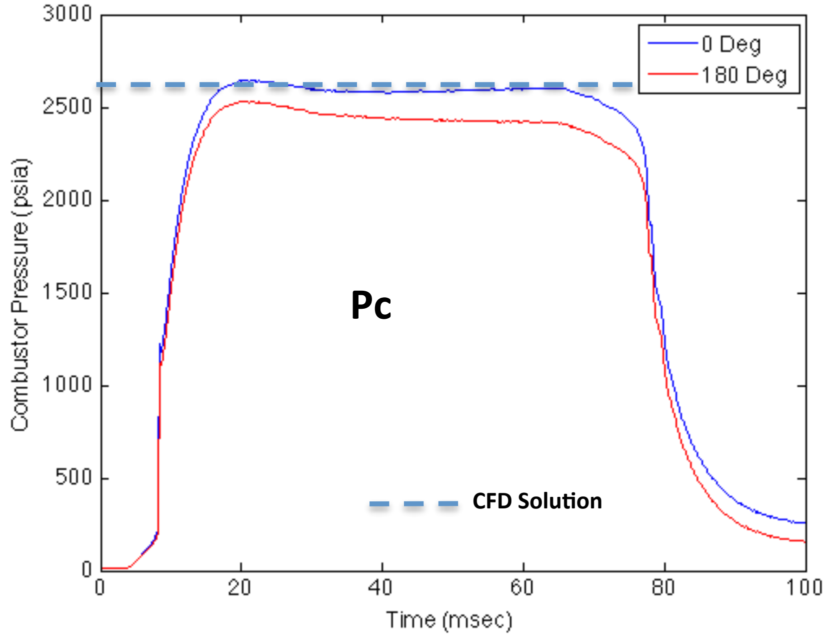
Internal engine instrumentation installed by CUBRC to determine performance and validation of design methodology

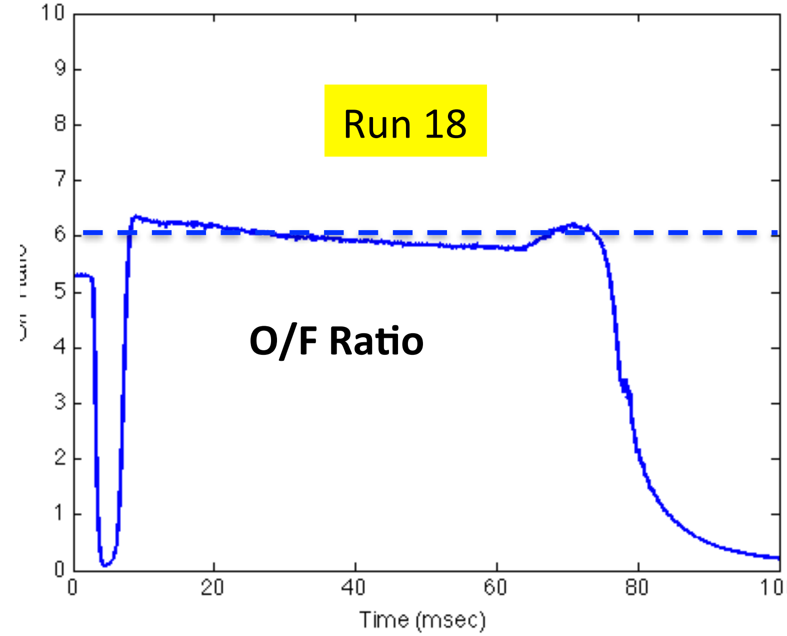
- **Initial design based on in-house engineering codes and assessment:**
  - QICE – engine component sizing/design & performance
  - IBFF – state parameter time history prediction code of the model performance
  - Valve-venturi design & performance code
  - Heritage design comparisons
- **Final design based on in-house CFD internal flow modeling of propulsion system:**
  - Combustion Instability Assessment
  - CUBRC developed CAD geometry
  - Loci-CHEM – CFD Code with finite-rate chemistry
  - Led to re-design of GO2 manifold system and combustor
  - Provided performance curves
- **Final design based on thermal modeling**
  - Patran/Sinda G – Led to nozzle material and coating selection
- **Developed nozzle specific enthalpy flow code**
  - Determines the nozzle exit specific enthalpy profile, the required test duration and material selection
- **Loads FEA**
- **Extensive design & analysis efforts were done to minimize cost and schedule risks.**

ATA-002 CS-REM



ATA-002 CS-REM Performance Analysis



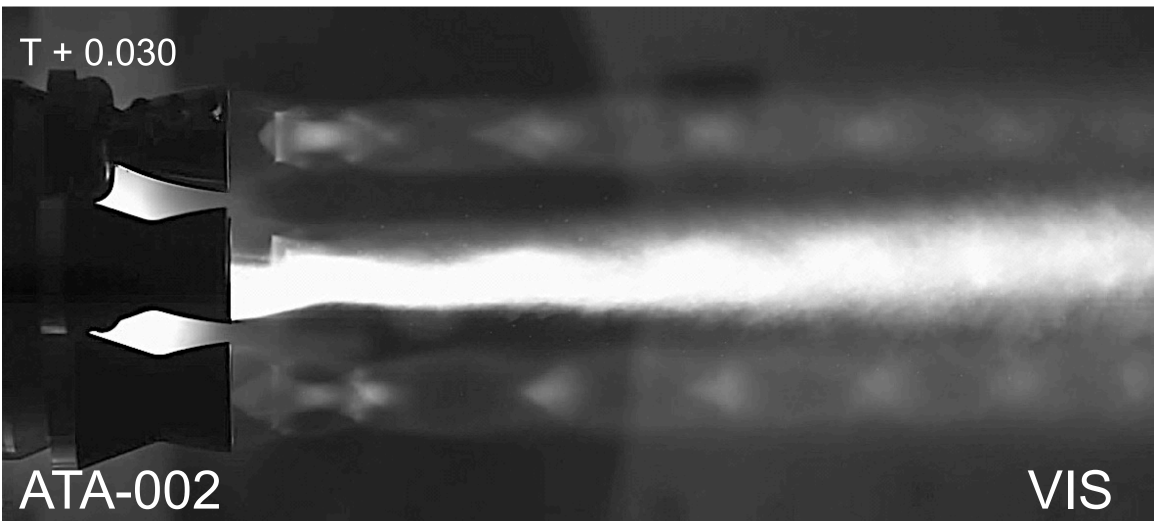


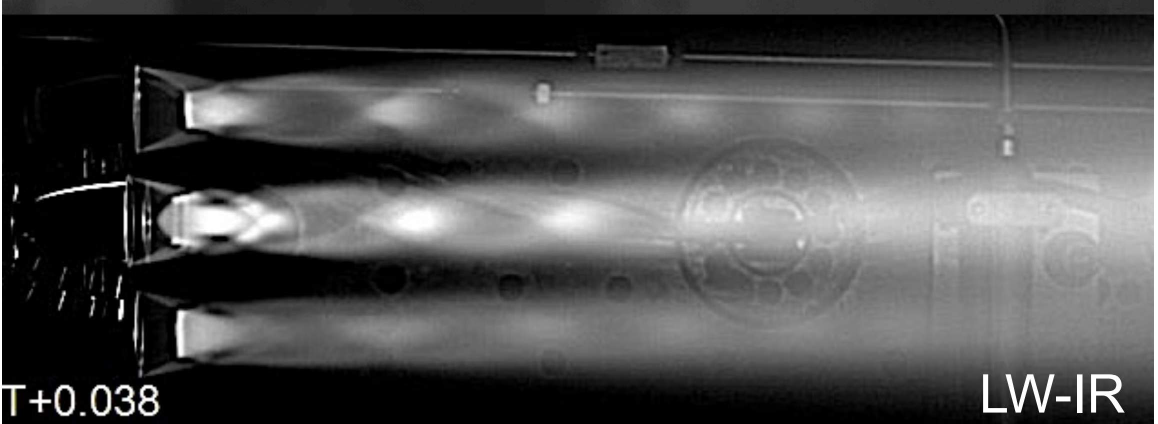
- **All performance parameters:**
  - Have met design requirements
  - Show good agreement with EV33 prediction and design tools
  - Show similarity to full-scale RS-25D engine system
- **All engine pressure measurements obtained by PCB-111 quartz gauge**

ATA-002 CS-REM Hot-Fire Test

CS-REM Plume

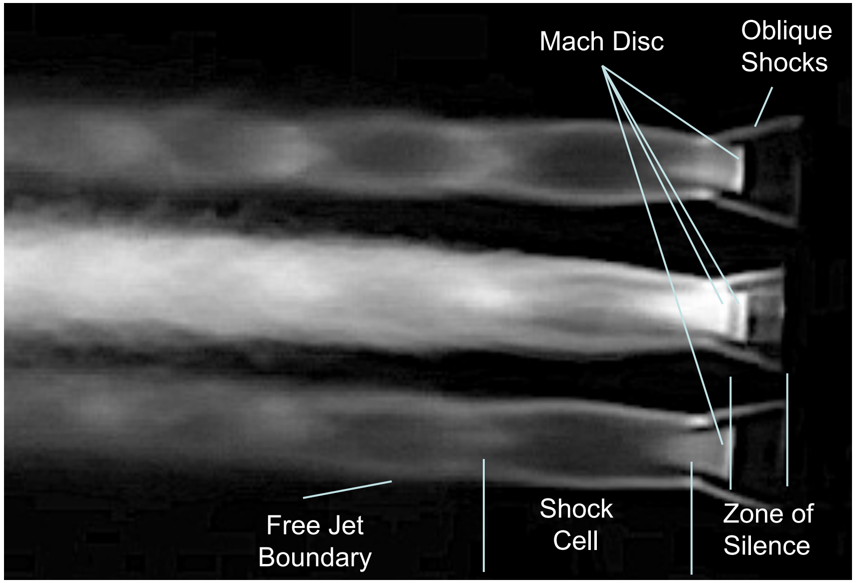
- MSFC camera provided high-resolution (1280 px x 800 px) and high frame-rate (16000 Hz) visible (VIS) video of CS-REM hot-fire tests
- MSFC infra-red (IR) camera provided long-wave IR video of CS-REM hot-fire tests
- Able to adequately determine the shock structure and flow physics

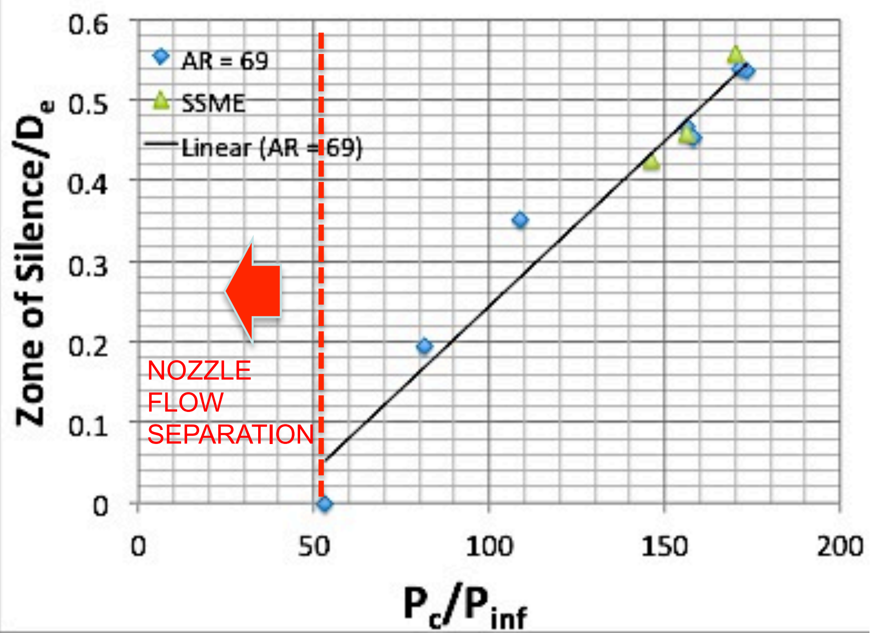


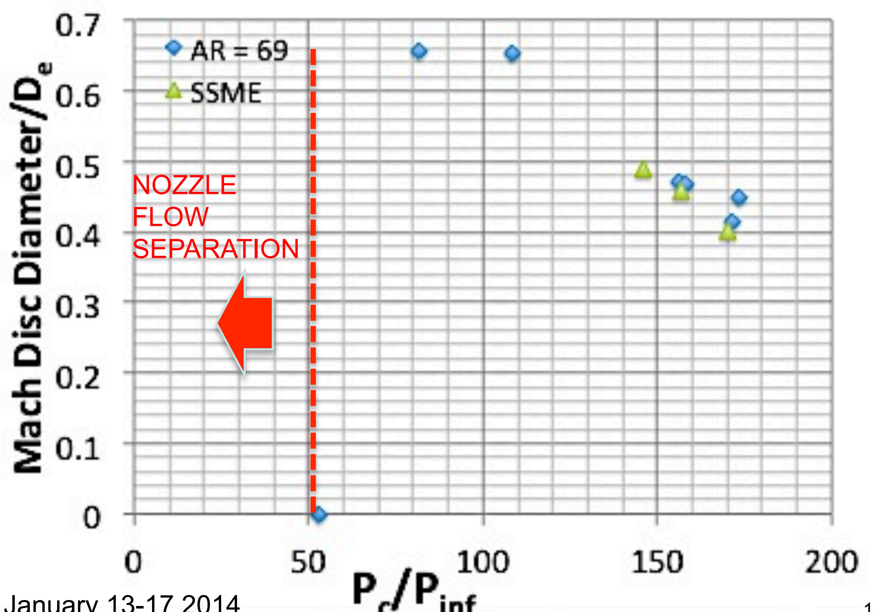


- SSME VIS video taken during static sea-level testing at NASA Stennis Space Center

CS-REM Plume Analysis

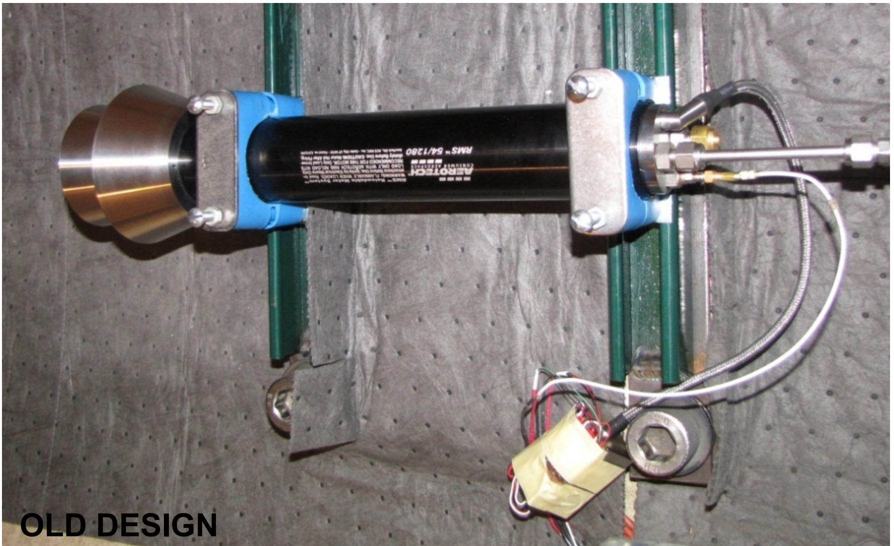


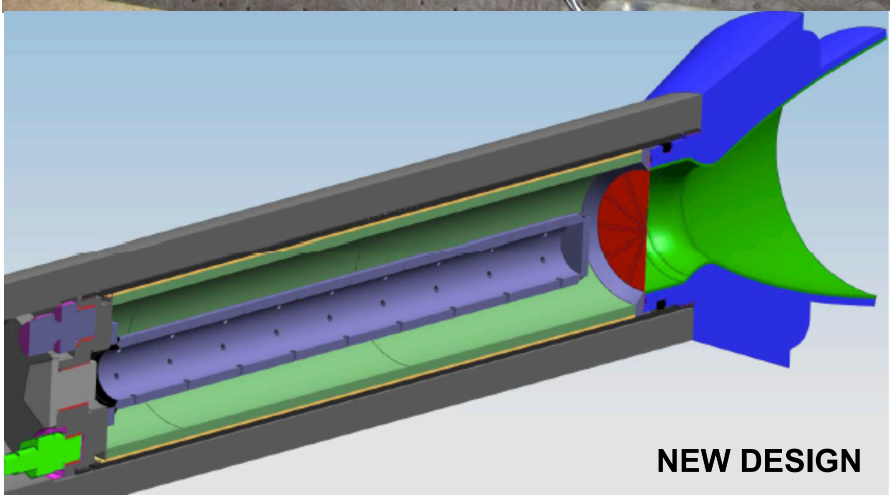




- **CS-REM plumes:**
  - Are over-expanded at sea-level conditions
  - Free-jet boundary converge toward the centerline
  - Develops a characteristic Mach disc
  - No plume-plume interactions observed
- **CS-REM shock structure and flow physics show good similarity with full-scale RS-25D (SSME) systems.**
  - Important to obtain high-fidelity base heating data
- **Zone of silence normalized distance increases linearly with chamber pressure.**

ATA-002 Booster Solid Rocket Motor (BSRM) Design





Internal engine instrumentation installed by CUBRC to determine performance and validation of design methodology

- **Initial design based on in-house engineering codes:**
  - Conservation of mass sizing/design & performance code
  - Heritage design comparisons
- **Final design based on thermal modeling**
  - Patran/Sinda G – Led to nozzle material and coating selection
- **Developed nozzle specific enthalpy flow code**
  - Determines the nozzle exit specific enthalpy profile, the required test duration and material selection

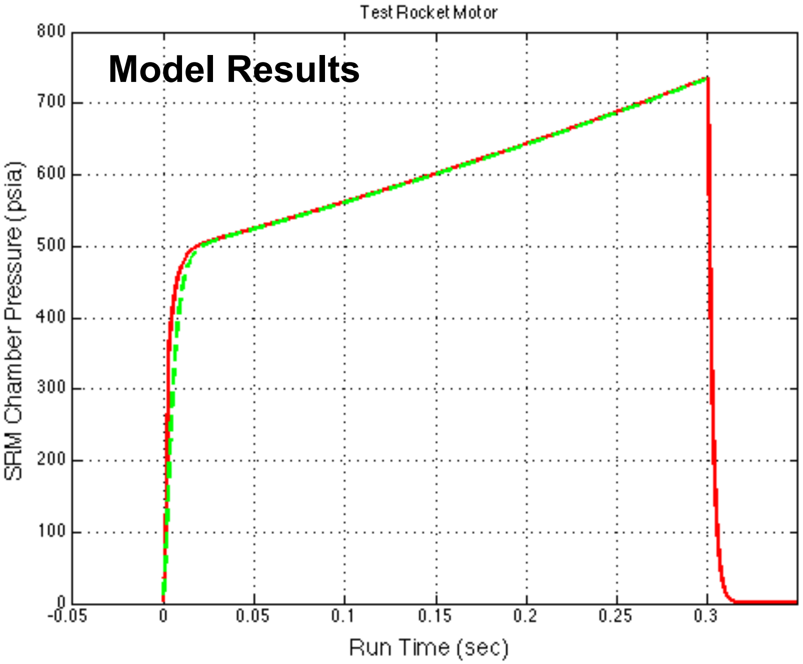
- **Initial design did not meet performance requirements due to significant ignition delay**
  - Required trial-and-error igniter options to obtain desired ignition response time
- **CUBRC with NASA MSFC collaboration developed an innovative igniter to meet design requirements**

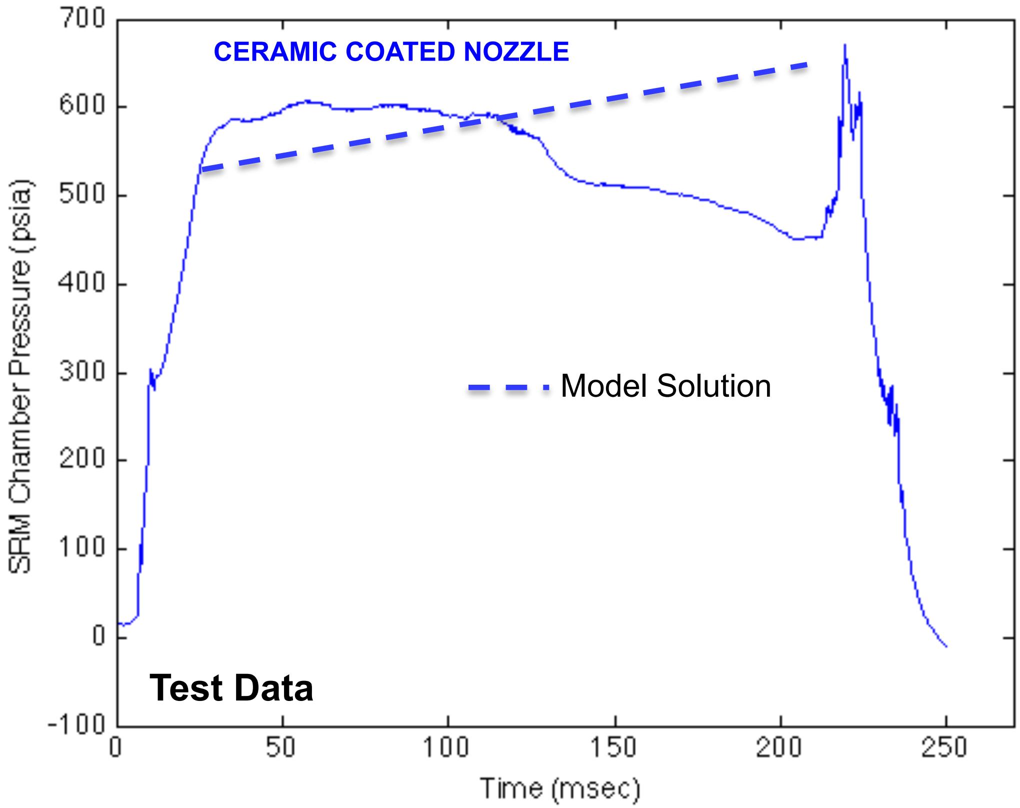
ATA-002 BSRM

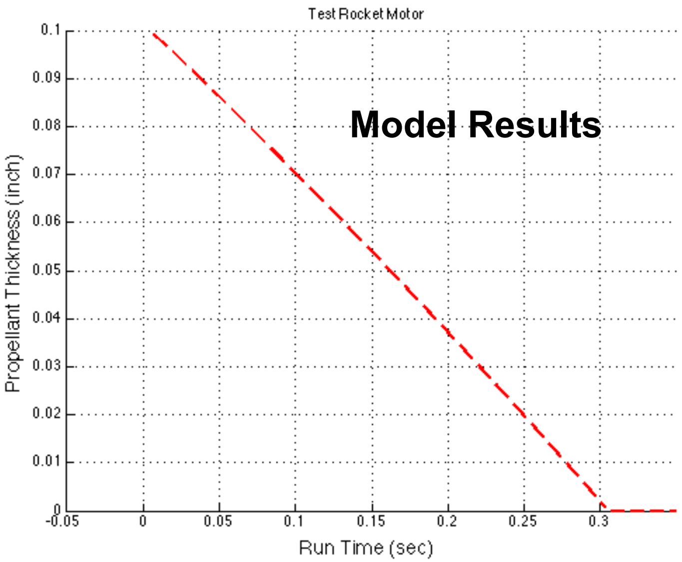




ATA-002 BSRM Performance Analysis



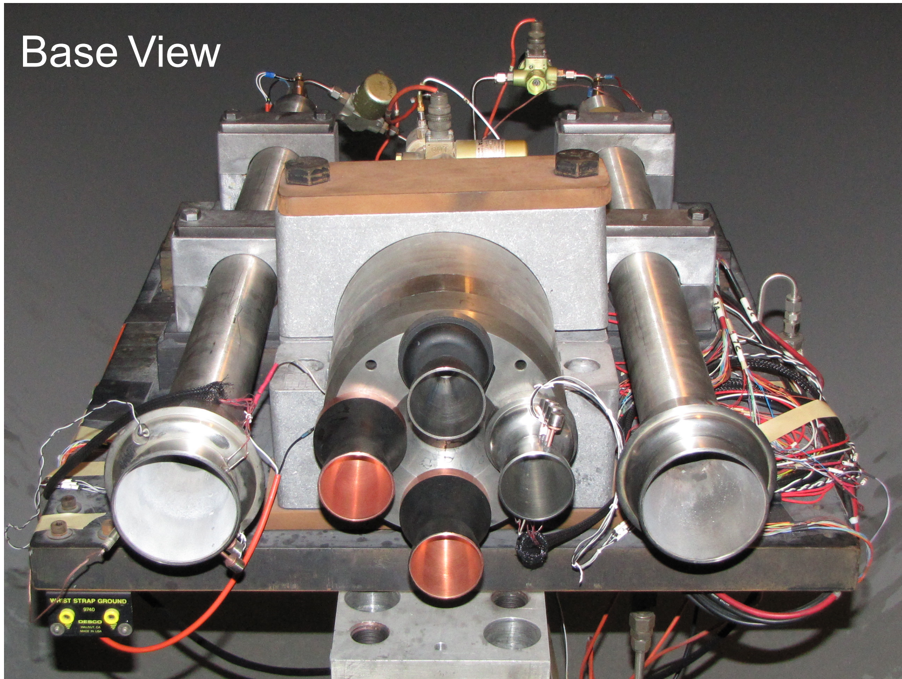


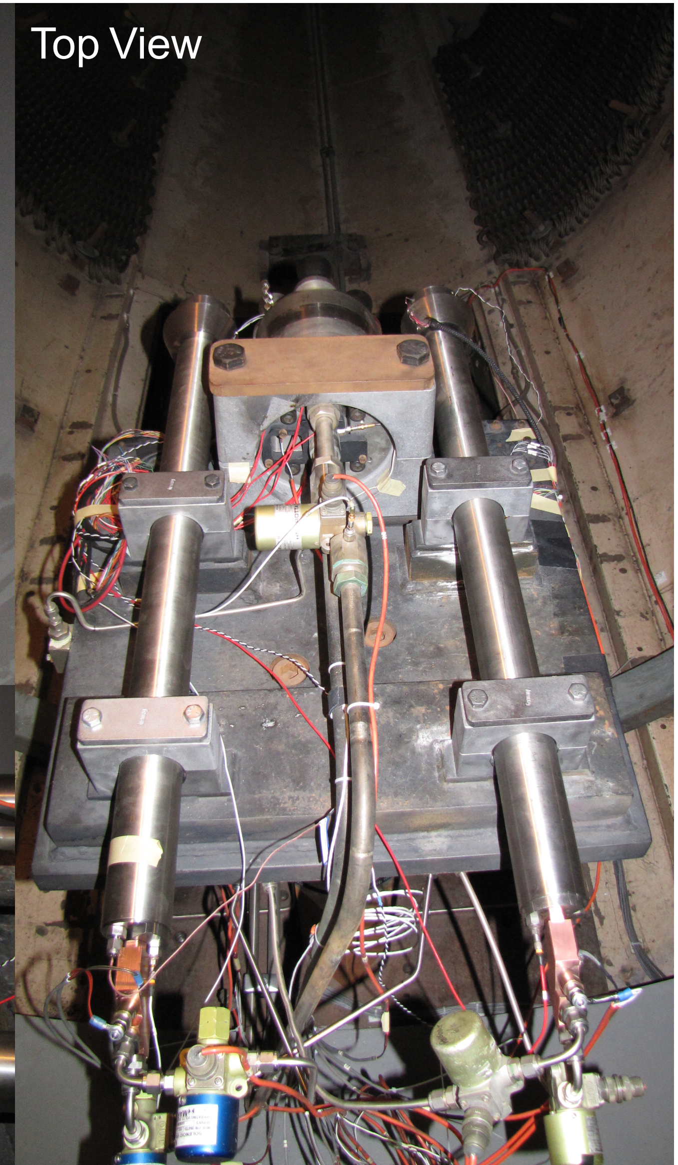


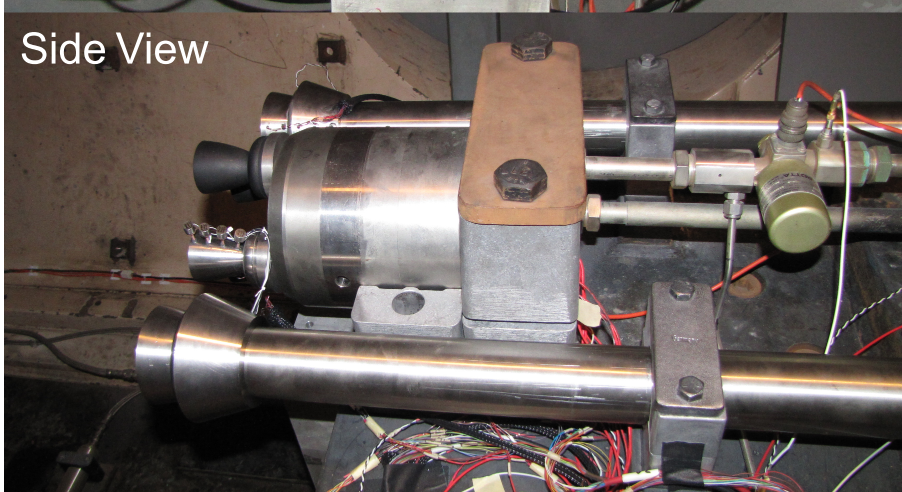
SRM Run 006
PROPELLANT X

	Pc Avg	T-shutdown	tau	Burn mass
	psia	*msec*	*msec*	*kg*
Model	550	300	25	0.42
Test	600	250	34	0.42

Integrated Core/Booster Stage Propulsion

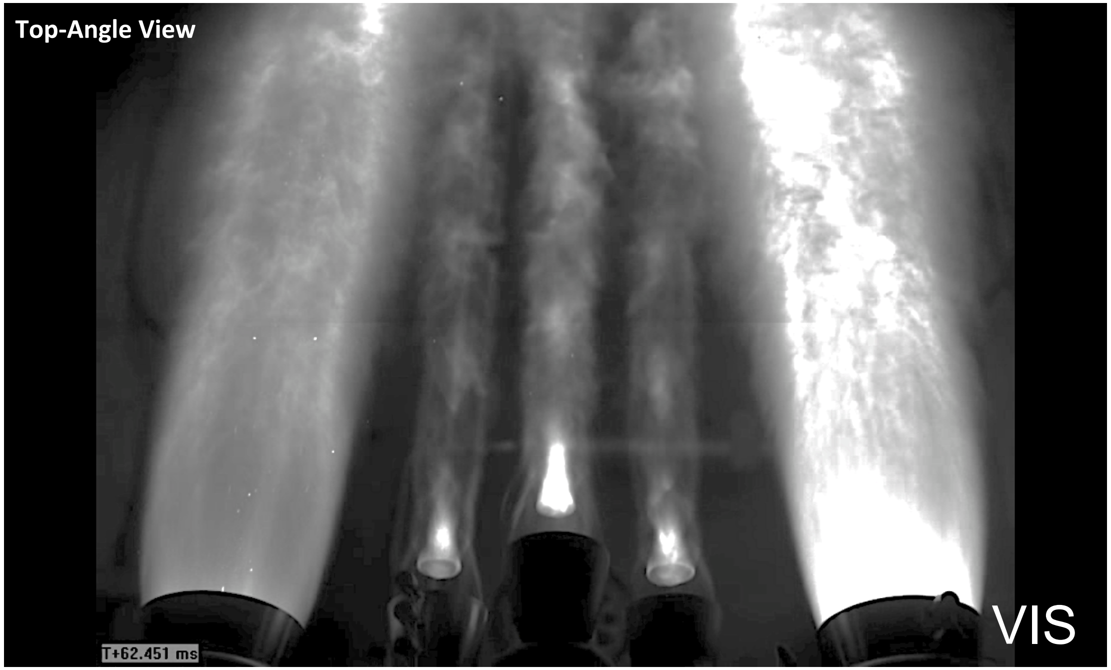




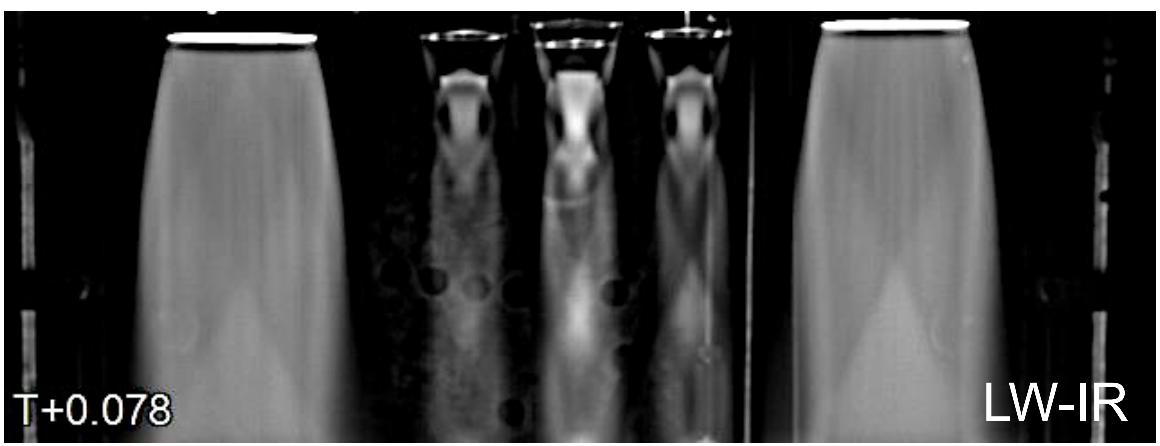


Integrated Core/Booster Stage Hot-Fire Test

Integrated Core/Booster Stage Rocket Plumes



RIGHT SOLID ROCKET MOTOR | CORE-STAGE ROCKET ENGINES | LEFT SOLID ROCKET MOTOR



- CUBRC VIS camera 4700 fps at 800 px x 600 px resolution
- VIS and LW-IR videos show CS-REM and BSRM plumes all-firing together as designed.
- All CS-REM plume Mach discs are within the same location and have the same diameter
- Plumes are fully-developed and steady in less than 35 msec
- Plume diameters are similar between the left and right BSRMs
- No flow asymmetry observed
- Showed propulsion designs are successful.

Conclusions

- **ATA-002 Technical Team has successfully designed, developed, tested and assessed the SLS Pathfinder propulsion systems for the Main Base Heating Test Program.**
- **Major Outcomes of the Pathfinder Test Program:**
  - Reach 90% of full-scale chamber pressure
  - Achieved all engine/motor design parameter requirements
  - Reach steady plume flow behavior in less than 35 msec
  - Steady chamber pressure for 60 to 100 msec during engine/motor operation
  - Similar model engine/motor performance to full-scale SLS system
  - Mitigated nozzle throat and combustor thermal erosion
  - Test data shows good agreement with numerical prediction codes
- **Next phase of the ATA-002 Test Program**
  - Design & development of the SLS OML for the Main Base Heating Test
  - Tweak BSRM design to optimize performance
  - Tweak CS-REM design to increase robustness
- **MSFC Aerosciences and CUBRC have the capability to develop sub-scale propulsion systems to meet desired performance requirements for short-duration testing.**

Acknowledgement & References

- *Special thanks to Mr. Mark D'Agostino (Aerosciences Branch Chief), Dr. Chris Morris (Aerothermal Team Lead), Mr. Jeff Vizcaino and EV33 for technical and programmatic support.*

- Mehta et al (2013), Numerical Base Heating Sensitivity Study for a Four-Rocket Engine Core Configuration, *J. of Spacecraft & Rockets*, Vol. 50, No.3.

- Detail information on propulsion design, fabrication, test and performance analysis will be published as a NASA Technical Memorandum.

Thank You

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